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THE FIDELITY ENHANCEMENT PROCESS

by

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The Fidelity Enhancement Process

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ABSTRACT

This study addresses the issues concerning the upgrade and reuse of computer simulation models and presents a comprehensive methodology — The Fidelity Enhancement Process — for conducting a model upgrade. Recent advances in software technology — specifically object-oriented programming and open architecture system development — have made this process feasible and provide unprecedented opportunities for model reuse. The Fidelity Enhancement Process was developed and applied to the Marine Corps Communication Architecture Analysis Model (MCCAAM) during its upgrade. MCCAAM simulates Marine Air Ground Task Force (MAGTF) single-channel communications architectures. MCCAAM was modified to evaluate architecture performance under different allocations of next-generation radios to units in the MAGTF, where the performance of an allocation was tactically driven.

TABLE OF CONTENTS

I. INTRODUCTION 1

A. STATEMENT OF THE PROBLEM 1

B. PURPOSE AND SCOPE 2

C. APPROACH 2

II. BACKGROUND 4

A. DEFINITIONS 4

B. OBJECT ORIENTED SIMULATION 4

C. OPEN ARCHITECTURE 6

D. MCCAAM 7

E. RISK MANAGEMENT 8

III. FORMULATION OF THE PROCESS 10

A. THE FIDELITY ENHANCEMENT PROCESS 10

B. STAGE 1 - THE MODEL ASSESSMENT 11

C. STAGE 2 - FIDELITY ENHANCEMENT REQUIREMENTS 13

D. STAGE 3 - PROTOTYPING 13

E. STAGE 4 - FIDELITY ANALYSIS 14

1. Fidelity Costs 14

a. Performance Degradation 14

b. Model Sophistication 15

c. Data Risk 15

2. Fidelity Benefits 16

3. Fidelity Assessment 17

F. STAGE 5 - FIDELITY DECISION 19

IV. APPLICATION OF THE PROCESS 21

A. BACKGROUND 21

B. STAGE 1 - THE MODEL ASSESSMENT 22

C. STAGE 2 - FIDELITY ENHANCEMENT REQUIREMENTS 22

1. Jammer Object 22

2. Mean Time Between Failures 23

3. Perishability 23

D. STAGE 3 - PROTOTYPING 24

E. STAGE 4 - FIDELITY ANALYSIS 24

1. Fidelity Costs 24

a. Jammer Object 24

b. Radio Failures 25

c. Message Perishability 25

2. Fidelity Benefits 25

3. Fidelity Assessment 25

a. Selection of Alternatives 25

b. Experimental Design 26

c. Weight Determination 34

d. Results of the 2^3 Experiment 34

F. STAGE 5 - FIDELITY DECISION 36

V. CONCLUSIONS AND RECOMMENDATIONS 37

A. CONCLUSIONS 37

B. RECOMMENDATIONS 38

LIST OF REFERENCES 39

APPENDIX A: DATA 40

APPENDIX B: INTERACTION PLOTS 72

INITIAL DISTRIBUTION LIST 75

I. INTRODUCTION

A. STATEMENT OF THE PROBLEM

In the current state of computer simulation, a model's ability to perfectly replicate the system being modelled is limited by time: a hardware based constraint. This limitation is continuously being reduced by advancing technology, which provides ever greater computing speed and quicker memory access. At the same time, software design improvements have given us the ability to modify and reuse existing models to meet new requirements.

Combined, these capabilities place great power in the hands of the analyst and give him a wide range of options for improved model design and expanded model usage. Of special interest is the ability that this increased power gives the analyst to upgrade existing models — to make good models even better. The big question becomes: how do we determine where best to apply our expanded capability to achieve this goal?

It seems appropriate to focus on areas of the model that were previously limited or ignored because of hardware or software constraints. It also makes sense to update the model to reflect any changes in the real world system that it represents; this may require changing the model's parameters or structure. The exploration of new model uses may also merit some of the available power. How do we choose from among these alternatives? The extent of the improvements to apply to each submodel is still another complicated decision. It appears that all of these issues must be addressed to effectively exploit the available power. The need for a coherent, scientific method to choose which submodels to upgrade is apparent, but there is no methodology available today that addresses these issues in an organized manner.

B. PURPOSE AND SCOPE

The purpose of this thesis is to develop a structured methodology for upgrading an existing model. The importance of such a methodology can be measured in terms of the time and money saved by not developing new models. The methodology concentrates on the questions posed earlier including: which parts of the model should be improved? and how much improvement does each part need?

In scope, this thesis is limited to developing a generic methodology and applying it to upgrade a single model — the Marine Corps Communication Architecture Analysis Model (MCCAAM) — which was developed at the Naval Postgraduate School by a team of analysts, including the author. The model simulates Marine Air Ground Task Force (MAGTF) single-channel communications architectures. MCCAAM was modified to evaluate architecture performance under different allocations of next-generation radios to units in the MAGTF, where the performance of an allocation was tactically driven.

C. APPROACH

New software technology — specifically object-oriented programming and open architecture (both described below) — have provided unprecedented opportunities for model reuse. It has become easier (and perhaps cheaper) to build and try model improvements than to determine *a priori* which improvements are worth pursuing. This thesis seeks to exploit these software innovations by presenting an organized methodology for identifying the model enhancements that might be worthwhile, building and evaluating prototypes of these enhancements and retaining only those deemed worthy.

II. BACKGROUND

A. DEFINITIONS

Before exploring the background material, some definitions are provided to bind the concepts and ideas that follow.

A model's level of **fidelity** is the degree to which the model produces the same outcomes as the tangible physical system it represents. Therefore a model with infinite fidelity would produce results identical to those of the actual system.

Aggregation is the extent to which a group of things in the real world have been consolidated in the model. A model that depicts an army in conflict as a single entity (object) is highly aggregated, whereas the depiction of 500,000 unique soldier objects represents total **disaggregation**.

Model **resolution** is the degree to which submodels are disaggregated. Resolution is the generic level of disaggregation within a submodel. Increasing resolution means replacing simple decision logic with more complex logic, using more source data, including more objects, or simply improving approximations at the cost of computational performance. Generally, a high resolution model also has high fidelity.

B. OBJECT ORIENTED SIMULATION

Object oriented simulation (OOS) provides a rich and easily understood environment for building computer models of real world systems. MCCAAM was written in MODSIM II, a general purpose, modular, high-level programming language that provides direct support for object-oriented programming[Ref. 1]. The following discussion of object oriented simulation uses MODSIM II terminology.

The modular structure of OOS directly supports model reuse by allowing programs to be constructed from library modules. Each library module contains a **Definition Module** outlining the type declarations and an **Implementation Module** that includes all of the executable code for the methods and procedures. This structure enables the developer to easily improve or modify one module with minimal impact on the remainder of the model and minimal additional development costs. The modular design of library modules and the objects they describe provide tremendous potential for comprehension and eventual reuse by the user as well as the designer.

An "**object**" combines a data record, which describes the state of the object, with procedures that describe its behaviors[Ref. 1]. The procedures are discussed first. They are called methods, and they describe the actions that the object can perform. The **ASK METHOD** in MODSIM II is equivalent to a procedure call in most languages: the actions are executed immediately, without passing any simulation time. The **TELL METHOD**, on the other hand, is executed asynchronously: the simulation continues for some time after a TELL METHOD has been called and during its execution. This allows a TELL METHOD to pass simulation time as a part of its actions. While the object's methods represent its actions, its state is reflected by its fields.

An object's fields are much like those of a normal record structure except that they can only be modified by the object's own methods. This enables the model developer to exercise total control over the changes made in these fields. Problems become easier to identify since they must be in that object's own methods. Although these values can not be changed by other objects, they can be "read" by other parts of the program.

This reference to other parts of the program brings up questions about the structure of the program. The single object described above is merely an **object type** with specified fields and methods. The object type serves as a template or specification. **Object instances** are created from it, dynamically, during the simulation. Once an object instance is created, its methods can be invoked by messages from other objects that ask it to perform its methods.

After an object type has been defined by its library modules, new types can be evolved from it. Each descendent in the resulting hierarchy can add its own fields and methods to those of its ancestors or modify an inherited method. Thus, if we take a collection of objects which share Vehicle Object as their ancestor and ask each to refuel, the Car Object might take on unleaded gas, the Truck Object diesel fuel and the Mule Object would eat hay[Ref. 1]. The capability of performing different actions with the same command is referred to as polymorphism. Combined with inheritance, it forms a solid foundation for reusing these object types.

C. OPEN ARCHITECTURE

In addition to OOS, a second major software technological advance is the move toward open architecture system development. Because of the new degree of standardization produced by open architecture, models are portable between computing architectures to an unprecedented degree. The term *open architecture* implies that some degree of standardization has been achieved in

- operating systems,

- graphical user interfaces,
- data base management interfaces,
- network operations and protocols, and
- interfaces to presentation graphics programs.

Open architecture provides the potential for model migration to improve performance or to realize any necessary capability upgrades. Reimplementing existing models on new architectures will no longer require developers to change the model's code. This alone represents a tremendous savings in simulation effort that can be applied to upgrading existing models rather than recoding models to support migration.[Ref. 2]

D. MCCAAM

The Marine Corps Communication Architecture Analysis Model (MCCAAM) simulates Marine Air Ground Task Force (MAGTF) FM single-channel radio communication architectures. The model uses a workload paradigm of Marine Broad Operational Tasks (MBOTS), Broad Operational Subtasks (BOSTs) and Message Exchange Occurrences (MEOs). This framework has been fitted to all of the standard message traffic within the Marine Corps[Ref. 3].

An **MBOT** encompasses a broad mission area and contains related tasks such as the MBOT *Artillery Call For Fire*. Each MBOT is further broken down into **BOSTs**, which represent specific tasks that are executed by units of specific types. For example, the *Standard Call For Fire* is one of the BOSTs contained in the MBOT

Artillery Call For Fire; it is initiated by a *Battery Forward Observer*. Each BOST is made up of a set of precedence constrained communications requirements, its MEOs.

An **MEO** specifies the unit types of the receivers as well as the net type used for its transmission. The first MEO of the *Standard Call for Fire* is a transmission from the *Forward Observer* to the *Battalion Fire Direction Center* on the *Battalion's Conduct of Fire* net. This traffic structure allows the model to generate realistic, interdependent message traffic.[Ref. 4]

E. RISK MANAGEMENT

The early identification of risk areas is crucial to the successful completion of any software development effort. **Risk areas** encompass logic, algorithms, data, and their associated assumptions.

The importance of risk management to military modelling is documented in the DoD Standard on Software Development, which calls for the documentation and implementation of procedures for risk management[Ref. 5]. The Risk Management Plan provides a useful framework for overcoming major sources of program risk.

A Risk Management Plan ensures that each project makes early identification of its top risk areas. These risk areas include potential cost and schedule problems as well as the technical risks mentioned earlier. It is important to develop a strategy for resolving these risk areas early in the development process. In addition, continuing emphasis should be maintained through periodic reviews and the resolution of new risk areas as they surface. Proper use of risk management will ensure the appropriate focus on early prototyping, simulation, key personnel staffing measures and other risk resolving techniques. This risk-driven approach helps the developer avoid problems that might otherwise jeopardize a successful model upgrade[Ref. 6].

III. FORMULATION OF THE PROCESS

A. THE FIDELITY ENHANCEMENT PROCESS

The Fidelity Enhancement Process is a risk-driven approach to increasing the resolution of an existing simulation model. The use of OOS and open architecture provide the flexibility needed by the developer to efficiently upgrade an existing model with this process. As a result, the process is directed primarily toward models that have been implemented in OOS environments that support open architecture.

Models that do not meet these criteria present limited opportunities for reuse. The model's lack of flexibility is detrimental to its reuse and may preclude any upgrade whatsoever. In fact, reimplementing these models in the desired format may not be possible due to the general incompatibility between most high level languages and object oriented programming languages. Compatibility problems between differing OOS environments may also preclude language changes. However, incorporating a newer version of the current programming language or a compatible graphics package are valid changes that can be implemented.

The five stage Fidelity Enhancement Process is a comprehensive methodology for upgrading existing computer simulation models. It is formulated for simulations that produce a decision from a finite set of alternatives. The stages are executed consecutively as portrayed in Figure 1.

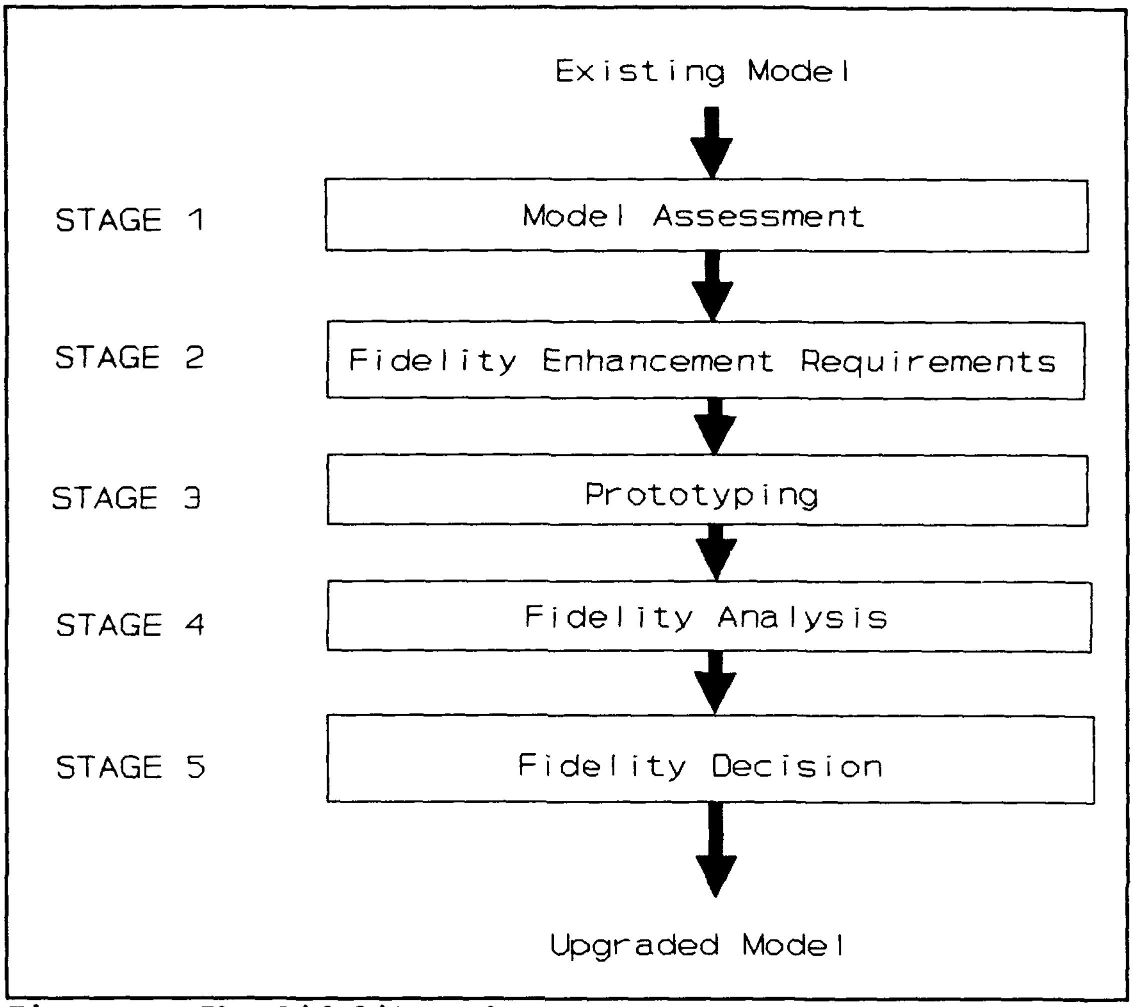

Figure 1 **The Fidelity Enhancement Process**

B. STAGE 1 - THE MODEL ASSESSMENT

The model assessment stage establishes the foundation and limits of the fidelity enhancement. The current capabilities of the model make up its foundation, and the circumstances which motivate the upgrade establish the limits. These limits are either hardware-driven, model-driven or a combination of both. Before exploring the limits, it is important that we ensure the foundation is sound.

The first step of the model assessment updates the risk areas within the current model. Risk areas encompass logic, algorithms, data, and their associated assumptions. These risk areas were used by the model developer to justify the model's current level of resolution. Although they were acceptable when the model was delivered, new data, requirements or standards may invalidate key assumptions that were made or logic that was used. Any discrepancies must be addressed at this point to ensure a strong foundation prior to setting the model upgrade limits.

With the foundation in place, the model upgrade limits are determined by analyzing the events which generated the need for a better model. Improvements in the computer hardware used by the model are the primary force behind a hardware-driven upgrade. In this case, the user's primary goal is to effectively utilize the increased capability. Closely related is the desire to migrate the model to a larger machine, such as a move from a PC to a workstation. In either case, the hardware issue becomes one of known dimensions, which are specified by the end user.

Model-driven upgrades involve the addition of specific capabilities or the enhancement of existing capabilities. This case is the most likely scenario, because historically simulation models have focused on specific problems under specific conditions. The need to solve a related problem under the same or changed conditions presents an opportunity for a model-driven upgrade. The limits of this upgrade may encompass both software and hardware issues.

This combination emphasizes the flexibility of open-architecture. Although the hardware currently supporting the model may offer some potential for expansion, the option may exist to migrate to a more capable machine. This combined option presents the opportunity to maximize the number of potential enhancements while holding down any resultant degradation of model performance.

C. STAGE 2 - FIDELITY ENHANCEMENT REQUIREMENTS

Requirements development begins with the definition of possible upgrade requirements. These represent both the end-user's "wish list" and the developer's vision of the next version of his model. Both may include new or modified user interface requirements as well as additional model capabilities. These needs are consolidated into a requirements list, which is developed jointly by the end user and developer. It includes all of the proposed model enhancements and their risk areas.

Once all the requirements have been identified, the steps required to implement each of them are outlined by the developer. They include the changes to the model for each requirement and their impact on the associated risk areas. This information is used by the developer as he formulates the specific modifications needed to add the proposed enhancements to the existing model. These modifications may include the addition of new modules or objects to the model as well as the modification of existing modules.

D. STAGE 3 - PROTOTYPING

The fundamental benefit provided by this model upgrading process is the ability to incorporate enhancements while minimizing the changes required to the current model. This integration of enhancements is accomplished through prototyping. Although the word "prototype" brings to mind the experimental version of a system used during preliminary design work, its potential as a tool for fidelity enhancement goes well beyond that limited view.

The prototyping necessary for the Fidelity Enhancement Process is **strawman prototyping**, which provides a surrogate system that can be investigated to improve the design of the eventual upgraded system[Ref. 7]. Each enhancement on the requirements list is integrated into the existing model in such a way that it can be turned on and off with software switches. This enables the developer to assess the impact of each enhancement combination on the model's overall performance.

E. STAGE 4 - FIDELITY ANALYSIS

Once the prototyped enhancements are in place, the developer must assess the costs and benefits of his new enhanced model. The underlying assumption of fidelity analysis is that by increasing model resolution, the model's fidelity must also increase. While the result of increased model fidelity is a better model providing better answers, the costs incurred by fidelity enhancement must also be addressed.

1. Fidelity Costs

Any increase in model fidelity produces a corresponding decrement to the execution of the model in terms of computing speed, the amount and types of data required and model sophistication. These decrements represent the **fidelity costs** inherent in the fidelity enhancement process. Other than the relatively low software modification costs, what exactly are these fidelity costs?

a. Performance Degradation

It is easy to predict that the enhanced model will experience longer execution times if it is run on the current hardware. But, the improved speed of newer hardware may compensate for the longer execution times. Therefore, model migration is one option that should be considered. A move to a more capable machine may be necessary to realize the needed enhancements. However, this move must be approved in advance by the end user to verify his ability to support the new hardware requirements. The developer must then test the enhanced model on the proposed platform and budget his expanded capability accordingly.

b. Model Sophistication

To increase the detail of a submodel, the developer increases the required level of understanding for himself and the user. Although the user has the option of viewing the submodel as a "black box", the acceptance and confidence in the answers rendered will normally necessitate the user's comprehension and understanding of the model's risk areas. His ability to effectively utilize an enhanced user interface may also depend on thorough understanding of the model's internal processes. The developer, on the other hand, must be an expert. His expertise should encompass the physical system being modelled as well as the model itself. This knowledge is crucial to the definition and application of the appropriate parameters to the model. Any shortcomings in this area also increase data risk.

c. Data Risk

Data risk derives from the effects of increased resolution on the data required to run the enhanced model. One effect is the need for additional data to support the greater level of detail being modelled. Another effect is increased sensitivity to the accuracy of the data. The developer and user are often called upon to estimate the parameters or even the probability distributions used by the model.

The degree of confidence (or lack thereof) in the user's ability to obtain the data and the quality of the sources make up an enhancement's data risk.

Unlike the first two fidelity costs, certain data risks can be addressed through sensitivity analysis. The ability to quantify these risks or demonstrate their limited impact may alleviate their costs. This is accomplished by varying the enhancement's parameters to gauge the model's response. It may also be useful to test each enhancement with varied parameters. Each variant would be tested as a separate enhancement. These related variants would then be compared to determine the sensitivity of the enhancement to its parameters. This analysis would take place in conjunction with the determination of the fidelity benefits.

2. Fidelity Benefits

The fidelity benefits from individual enhancements manifest themselves as incrementally better answers to the questions being asked or choices being made. This higher resolution level may raise the end-user's confidence in, and acceptance of, the model's decisions. Depending on the upgrade involved, the model may answer new, more detailed questions or provide more detailed answers to existing questions. Another area that may benefit from the upgrade is the accuracy of the decision rendered. These possible effects are dependent on the particular model and seem difficult to quantify. But the ability to quantify the fidelity benefit or yield of each enhancement is crucial to the Fidelity Enhancement Process. This quantification is the focus of the fidelity assessment.

3. Fidelity Assessment

The fidelity assessment is the cornerstone of the Fidelity Enhancement Process. It encompasses the collection and processing of all the fidelity costs and benefits. The assessment begins with the establishment of the test case, which includes the selection of the data sets necessary to run the model. Each of these data sets contain one of the model's **alternatives**, which is a possible solution that is compared to all of the other possible solutions to determine the best. Once the set of possible alternatives have been identified, the next step is to establish the decision boundaries.

The decision boundaries are established in terms of the baseline and topline cases. Each of these cases represent an **upgrade combination**: a combination of enhancements that are turned "on" and "off". The baseline case corresponds to no enhancements turned "on". This case produces an answer equivalent to that of the original model. The decision produced by switching all of the enhancements "on" is the topline case. This case represents the decision produced at maximum resolution. The first question to be answered is: are the baseline and topline decisions equal? If they are, the enhancements have produced an insignificant increase in model fidelity and should be left out of the model, avoiding their fidelity costs. If the decisions differ, the fidelity analysis continues with the determination of a weight for each alternative.

The model's decision output from the topline case is utilized to construct the weights used by the Measure of Performance (MOP) equation (below). A weight is determined for each of the alternatives outlined earlier. Each alternative's weight corresponds to the proportion of times it was chosen as the best alternative by the topline case.

$$W_j = \frac{T_j}{R}$$

j = *Alternative number*
W_j = *Weight of Alternative j*
T_j = *Number of Alternative j decisions*
R = *Number of Replications*

The MOP can then be calculated for each proposed upgrade combination by running R replications of the model and summing the products of the weights and the number of times each alternative was chosen.

$$MOP_i = \frac{1}{R}\sum_{j=1}^{n} A_{ij} W_j$$

i = *Upgrade Combination Number*
j = *Alternative Number*
MOP_i = *Measure of Performance for Upgrade Combination i*
A_{ij} = *Number of Alternative j Decisions*
W_j = *Weight of Alternative j*
R = *Number of Replications*
n = *Number of Alternatives*

The evaluation of these MOPs and the direction along which the fidelity assessment proceeds become model dependent at this point.

For an upgrade involving a relatively small number of enhancements, a 2^k factorial design is preferred. This special case of general factorial design is keyed to the comparison of factors with only two levels. In this case, "k" represents the number of enhancements while the two levels are "on" and "off". This type of analysis allows the analyst to more accurately gauge the interactions between the k factors and their effect on the model's response[Ref. 8]. For upgrades that entail numerous enhancements, the number of experimental runs required for a factorial design may become prohibitive. Alternate designs, such as two-stage designs or single factor analysis are more appropriate for these situations.

Single factor analysis treats each enhancement as an alternative system and discounts the interactions between them. Common examples of this technique include randomized complete block design and other forms of one way analysis of variance[Ref. [Ref. 9]. Or, as an alternative, the best of a group of similar enhancements may be chosen using "two-stage" sampling. This technique also treats each enhancement as an individual alternative. The analyst estimates the variance produced during the first stage. This is used to establish the number of runs required for the second stage, which produces the final decision[Ref. 9]. A slight modification of this technique selects a fixed number of best enhancements from the total[Ref. 9]. This method can be used to trim down the number of enhancements to a level more conducive to a factorial design. This brief look provides some ideas concerning different possibilities for enhancement analysis. It remains the job of the analyst to tailor this assessment to the characteristics and needs of his model upgrade and provide the decision maker with the data needed to make an informed fidelity decision.

F. STAGE 5 - FIDELITY DECISION

The fidelity decision stage consolidates the analysis of fidelity benefits with that of the fidelity costs. The end user then compares the enhancement yields with their associated performance decrements to the subjective analysis of model sophistication and data risk and makes his decision.

IV. APPLICATION OF THE PROCESS

A. BACKGROUND

The Fidelity Enhancement Process was applied to the Marine Corps Communication Architecture Analysis Model (MCCAAM). This proved beneficial even though MCCAAM was in its initial development.

MCCAAM is a computer simulation of Marine Corps single-channel radio architectures[Ref. 4]. It replicates the interactions between units, radios and nets in a realistic manner using the BOST message structure explained in section II D. The network architecture is constructed dynamically from the input data, which results in nearly unlimited flexibility: the model can be applied to radio networks of all types and sizes. A penalty process gauges the number of BOSTs that are not completed in a timely manner. Each BOST has an allotted time for completion after which the architecture is immediately assessed a BOST-specific one time penalty and then a (again BOST-specific) constant penalty rate until it is completed. This penalty process is used to assess the performance of a given architecture in terms of its long term penalty rate.

The original (baseline) model uses the internal penalty process to choose the best architecture from a finite set of alternatives. In addition to this capability, the problem of choosing the best allocation of new SINCGARS radios as partial replacements for current PRC-77 radios in an existing architecture was posed. This particular application of MCCAAM required enhancements that would differentiate between the two radio types.

B. STAGE 1 - THE MODEL ASSESSMENT

The model assessment proceeded rapidly because the upgrade was executed almost concurrently with the model's initial development. As a result, the risk areas were up to date, the model's foundation was sound and the boundaries were established during the original development effort.

The model's hardware boundaries were dictated by the software memory limitations of MODSIM's PC version and its C compiler. The model quickly outgrew that platform and was subsequently migrated to a SUN workstation with a newer version of MODSIM II. The previously encountered limitations were alleviated by this move, which was cleared by the end-user prior to its adoption by the developers.

C. STAGE 2 - FIDELITY ENHANCEMENT REQUIREMENTS

This model-driven upgrade resulted in the development of numerous enhancements including a new object, which portrayed the effects of enemy jamming systems, and changes to existing objects.

1. Jammer Object

The introduction of enemy jamming to the model was considered crucial because the newer SINCGARS radios have a frequency hopping capability that make them effectively "jam-proof", and this is the primary difference between the two radios. The new **Jammer** object type was developed as a generic specification that could be applied to any enemy jamming system. The parameters used to specify each jammer include its location and type as well as the jamming direction, range and duration.

2. Mean Time Between Failures

An additional discriminator between the two radios is the expected mean time between failures (**MTBF**). Test and evaluation of the new radio reflects a significant increase in reliability for the SINCGARS. In addition, the modular design of the SINCGARS radio gives it a shorter mean repair time. However, once the SINCGARS radio is repaired or replaced, the process of rejoining a frequency-hopping SINCGARS net requires significantly more time than rejoining a PRC-77 single frequency net. As a result, parameters reflecting the MTBF, repair time, and net entry time for each radio type were estimated. The radio object and its methods required modification to incorporate these changes.

3. Perishability

The developers found that the need for action following the loss of a radio or access to a net induced a complicated series of events. Although the routing of traffic on a functional network is relatively straight forward, the alternate routing procedures required to deal with enemy jamming and equipment failure proved to be very complex. Incorporating an algorithm to accomplish the alternate routing required the addition of a completely new module.

Bottlenecks formed in the network by the previously mentioned changes raised questions concerning the perishability of message traffic. A message that is trapped in an inoperational radio's queue may reach a point where its transmission is no longer a valid requirement. At this point, the message is considered **perishable** and is removed from the network. The enhancements required to implement this capability included the modification of the BOST structure and changes to the BOST data files.

D. STAGE 3 - PROTOTYPING

The enhancements described above were systematically added during model development. The software switches used to enable the enhancements could be switched on to work on the enhancements or off for unimpeded work on the baseline model. By adhering to this practice, the development of both proceeded with minimal conflict.

E. STAGE 4 - FIDELITY ANALYSIS

Three enhancements were implemented to differentiate between SINCGARS radio allocations: Jammers, MTBF, and Perishability.

1. Fidelity Costs

The fidelity costs incurred by the chosen enhancements include performance degradation, model sophistication and data risk. Performance degradation was measured in terms of clock time. A stopwatch was used to measure the extra time required for each of the enhancements. In addition, the subjective costs were evaluated for each of the enhancements.

a. Jammer Object

The addition of the jammer object introduced a great deal of model sophistication and data risk. The baseline model and its portrayal of the MAGTF radio network is comprehendible to anyone with experience in tactical operations. However, the proper application of electronic warfare to the model requires additional expertise on the part of the user. The choice of jammer type and employment strategy must be made during the creation of the jammer data file and prior to model execution. Data risk is generated by the choices previously mentioned as well as the jammer's parameters which, in this case, do not reflect terrain features or weather considerations.

b. Radio Failures

Although the sophistication required to utilize the radio failure enhancement is comparable to that required by the baseline model, there is some data risk involved. The actual MTBF is an estimated parameter as is the "repair or replace" time for each. Other data risk issues involve modelling the substitution of broken radios with spares or switching frequencies between nets on an operational radio.

c. Message Perishability

Message perishability is primarily data risk sensitive. These risks include a subjective judgement whether or not each BOST is perishable as well as the estimation of perishability points for those that are.

2. Fidelity Benefits

The fidelity benefits manifest themselves as better radio allocation decisions.

3. Fidelity Assessment

a. Selection of Alternatives

The fidelity assessment began with the specification of the allocation alternatives. A sample data set was developed that focused on the Ground Combat Element (GCE) of a Marine Expeditionary Brigade (MEB). The units, nets and BOSTs that were stressed involved indirect fire support and tactical communications. Three different radio allocations were chosen as possible solutions to the optimal allocation problem. These three radio allocations served as the **alternatives**.

Table I Allocation Alternatives

ALTERNATIVES		
Number	Description	# SINCGARS
1	FEBA Back Configuration	49
2	Top Down Configuration	53
3	All PRC-77 Configuration	0

The first two alternatives reflect the possible tactical employment of these communications assets on the battlefield while the third represents the current architecture. The forward edge of the battle area (FEBA) back alternative places the SINCGARS radios on those nets that are physically closest to enemy jamming assets and carry the bulk of the architecture's traffic load. These include nets of battalion level and lower. The top down alternative focuses the employment of SINCGARS radios in the nets controlled by higher headquarters. These nets normally have a greater number of subscribers and process the most important message traffic. The third alternative depicts the current tactical architecture with no SINCGARS radios employed. This alternative was added to judge the impact of no SINCGARS radios on the scenario and provide a measure of current architecture performance.

b. Experimental Design

A 2^k factorial experimental design was selected. The name 2^k relates to considering k factors each with two possible levels. This design allows the smallest number of treatment combinations with which k factors can be analyzed under a complete factorial arrangement[Ref.8].

A 2^k design may provide information on how sensitive the model's output is to the different enhancements. This design can also provide insight into the interactions between the enhancements. The design is particularly well suited to this fidelity analysis in that the enhancements are inherently two level (on and off).

The 2^3 design represents an experiment using three factors each with two levels. As stated earlier, the three factors analyzed were jammers, MTBF, and perishability. The incorporation of these three factors produced 8 possible treatment (upgrade) combinations.

Table II Treatment (Upgrade) Combinations

Upgrade Combinations		
index	code	description
1	000	Baseline Case (all off)
2	001	Jammers only
3	010	MTBF only
4	011	Jammers & MTBF
5	100	Perishability only
6	101	Jammers & Perishability
7	110	MTBF & Perishability
8	111	Topline Case (all on)

The **upgrade combinations** (UC) are indexed with i which ranges from 1 to 8. The code represents the actual enhancements incorporated within each upgrade combination. The three digits of the code correspond to the three enhancements portrayed as perishability, MTBF and Jammers in that order. The digits 0 and 1 correspond to off and on, respectively.

Each of the radio allocation alternatives were evaluated by MCCAAM under each of the 8 upgrade combinations. Each of these 24 (3 alternative x 8 upgrade combinations) model runs produced a steady state penalty plot that was analyzed using MCCAAM's analysis routines. This analysis was performed on the penalty rates (R_{ijk}) generated by each model run. The initial condition analysis established the steady state point at 700 minutes into the 10,000 minute run. The remaining 9300 minutes were sampled at 25 minute intervals to produce approximately 360 samples. The batch size was set at 12 to produce 30 iid batch means or penalty rates. The autocorrelation of these batches was analyzed and found to be insignificant(max ρ = .023120). Each vector of penalty rates was then broken down into five groups of six samples and tabulated in matrices.

Table III Sample R_{ijk} Matrix

UC 2	Samples (k=1,...,6) for Replication 1					
Alternative	1	2	3	4	5	6
1	R_{211}	R_{212}	R_{213}	R_{214}	R_{215}	R_{216}
2	R_{221}	R_{222}	R_{223}	R_{224}	R_{225}	R_{226}
3	R_{231}	R_{232}	R_{233}	R_{234}	R_{235}	R_{236}

$$R_{ijk} = \textit{penalty rate } k \textit{ of } UCi \textit{ and alternative} j\ ,\ k=1,\ldots,30$$

These penalty rates are then compared across the alternatives to determine the lowest penalty rate for each sample number. The variable T_{ijk} is used to denote the alternative with the lowest (best) penalty rate. The winner receives a one while the remainder of the alternatives get zeros.

$$T_{ijk} = 1, \text{ if } R_{ijk} < R_{ink}, \text{ for all } n \neq j$$
$$= 0, \text{ otherwise}$$

These values were then tabulated in the T_{ijk} table and the group totals were calculated by summing across the samples.

Table IV Sample T_{ijk} Matrix

UC 2	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	0	0	0	1	0	1	2
2	1	0	1	0	1	0	3
3	0	1	0	0	0	0	1

These group totals (A_{ijl}) reflect the number of times each alternative was selected as the best and range from zero to six. The group totals are used to calculate the Measure of Performance (MOP) values for each group. Once calculated, the group totals are tabulated in a group total matrix.

$$A_{ijl} = \sum_{k=l(1)}^{l(6)} T_{ijk}, \quad l = 1, \ldots, 5$$

i = *Upgrade Combination (UC) index*
j = *Alternative Number*
k = *Sample Number*
l = *Group Number*
A_{ijl} = *Number of Times Alternative j chosen for UC i in Group l*
T_{ijk} = *Lowest Penalty Rate for Sample k, 1 or 0*

Table V Sample Group Total Matrix

UC 2	Alternatives			
Group	1	2	3	Total
1	2	3	1	6
2	3	2	1	6
3	2	1	3	6
4	4	1	1	6
5	3	1	2	6

The measure of performance (**MOP**) for each upgrade combination is calculated by summing the products of weight and number of times chosen for each alternative. This sum is then divided by the group sample size to get the average value for each group. These 40 MOP values are then used to conduct an analysis of variance ANOVA.

$$MOP_{il} = \frac{1}{6} \sum_{j=1}^{3} A_{ijl} W_j \quad , for\ i=1,\ldots,8,\ l=1,\ldots,5$$

i = *Upgrade Combination (UC) index*
j = *Alternative Number*
l = *Group Number*
MOP_{il} = *Measure of Performance for UC i*
A_{ijl} = *Number of Times Alternativej chosen for UC i*
W_j = *Weight of Alternativej*

The weight for each alternative, W_j was calculated using the topline case as outlined in section III E 3. This weight represents the proportion of the time that an alternative was selected by the highest fidelity upgrade combination (the topline case). The group totals were summed for each alternative and then divided by the total number of samples (30) to determine each alternative's weight.

Table VI Treatment (Upgrade) Combinations

Upgrade Combinations			
index	code	description	MOP
1	000	Baseline Case (all off)	(1)
2	001	Jammers only	a
3	010	MTBF only	b
4	011	Jammers & MTBF	ab
5	100	Perishability only	c
6	101	Jammers & Perishability	ac
7	110	MTBF & Perishability	bc
8	111	Topline Case (all on)	abc

Once all of the MOP values have been determined, multifactor analysis of variance (ANOVA) was utilized to calculate the relationship between the response variable (fidelity yield) and the three factors. The model's accuracy depends on the assumption that the error terms are normally distributed and independent. The following linear equation was used to model this relationship.

$$Y_{ijkl} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \epsilon_{(ijk)l}$$

Y_{ijkl} = *lth response with factors at levels i, j, k*
μ = *overall mean response*
τ_i = *effect of Jammers at level i*
β_j = *effect of MTBF at level j*
γ_k = *effect of Perishability at level k*
ϵ_{ijkl} = *the random error component*
ijk = *factor level* (1 = *on*, 0 = *off*)
l = *sample number* (l = 1, . . . ,6)

In this design, the factors τ_i, β_j, and γ_k correspond to the three enhancements. The terms in parentheses indicate two-way $(\tau\beta)_{ij}$ and three-way $(\tau\beta\gamma)_{ijk}$ interactions of the corresponding factors. It is assumed that the random error terms, ϵ_{ijkl}, are independent, identically distributed normal variables with a mean of zero and a variance of σ^2[Ref. 8]. The treatment effects are defined as deviations from the overall mean so,

$$\sum_{i=1}^{2} \tau_i = 0, \quad \sum_{j=1}^{2} \beta_j = 0, \quad \sum_{k=1}^{2} \gamma_k = 0$$

Similarly, the interaction effects are fixed and defined so that they also sum to zero as shown below for the $(\tau\beta)_{ij}$ interaction.

$$\sum_{i=1}^{2} (\tau\beta)_{ij} = \sum_{j=1}^{2} (\tau\beta)_{ij} = 0$$

In this factorial design, all three factors are of equal interest. We are specifically interested in testing hypotheses concerning the equality of the treatment effects.

$$\begin{aligned} H_o &: \ \tau_1 = \tau_2 = 0 \\ H_1 &: \ \text{at least one } \tau_i \neq 0 \end{aligned}$$

We are also interested in the interactions between the treatments and therefore test each of the interaction terms.

$$\begin{aligned} H_o &: \ (\tau\beta)_{ij} = 0 \qquad \text{for all } i, j \\ H_1 &: \ \text{at least one } (\tau\beta)_{ij} \neq 0 \end{aligned}$$

These hypotheses are tested using a multifactor ANOVA. The sum of squares for each treatment as well as the total sum of squares (SS) is calculated and divided by its degrees of freedom to obtain its mean square. The expected values of the mean squares (MS) are

$$E(MS_A) = E\left(\frac{SS_A}{a-1}\right) = \sigma^2 + \frac{bn\sum_{i=1}^{2}\tau_i^2}{a-1}$$

$a = b = 2$ *levels*
$n = 5$ *groups of data*

If the null hypothesis for each treatment is true, then all of the expected mean squares estimate σ^2. However, if there are differences between treatment effects then that particular E(MS) value will be larger than the expected mean square error term $E(MS_E)$.

$$E(MS_E) = \sigma^2$$

Therefore, to test the significance of the main effects and their interactions, simply divide the corresponding mean square by the mean square error. Based on our assumption of independent identically distributed normal error terms with constant variance, σ^2, each of the ratios of mean squares are distributed as F with 1 degree of freedom in the numerator and 32 in the denominator. The critical region is then the upper tail of the F distribution. The procedure is summarized in the analysis of variance table in part d. of this subsection.

c. *Weight Determination*

The weights were calculated by using the topline case to generate decision output that reflects the highest level of fidelity. This data was transformed into proportions that reflect the frequency that the alternative was chosen.

Table VII Alternative Weights

Alternative	# Selections	Weight
1	18	.60
2	5	.17
3	7	.23

d. *Results of the 2^3 Experiment*

The experiment was performed as discussed in the part b. The penalty rate (R_{ijk}) and T_{ijk} matrices are consolidated in Appendix A. The Group Total matrices are also located in Appendix A. The MOP values (MOP_{il}) are displayed below.

Table VIII MOP Values

	Groups				
UC	1	2	3	4	5
1	.333	.333	.333	.333	.333
2	.323	.395	.343	.467	.405
3	.262	.343	.395	.405	.343
4	.272	.415	.405	.467	.282
5	.333	.333	.333	.333	.333
6	.323	.395	.343	.467	.405
7	.415	.467	.252	.405	.343
8	.395	.467	.395	.538	.415

These values were then analyzed using the multifactor ANOVA capabilities of Statgraphics version 5. The resulting ANOVA table revealed only one significant main effect and no significant interactions.

Table IX ANOVA Results

Analysis of Variance for Fidelity Yield					
Source of Variation	Sum of Squares	df	Mean Square	F-ratio	p
Main Effects					
A	.81796	1	.81796	6.579	.015
B	.20736	1	.20736	1.668	.206
C	.22801	1	.22801	1.834	.185
Interactions					
AB	.01156	1	.01156	.093	.766
AC	.05041	1	.05041	.405	.536
BC	.22801	1	.22801	1.834	.185
ABC	.05041	1	.05041	.405	.536
Residual	3.97872	32	.124335		
Total	5.57244	39			

The application of Jammers produced the only significant effect on the model's fidelity yield($p = .015$). The remaining two factors, MTBF and perishability produced roughly equivalent p values (.206 and .185 respectively) but were well above a conservative α value of .10. The interaction effects were even less significant with the exception of the BC term which corresponds to the interaction between MTBF and perishability. This term had a p value of .185 while the remainder were greater than 0.5. The interaction plots are in Appendix B.

F. STAGE 5 - FIDELITY DECISION

The fidelity analysis demonstrates clearly that only the Jammer enhancement should be added to the upgraded model. Its significance to the model is highlighted by the results of the multifactor ANOVA as displayed in Table IX. The fidelity costs of the remaining enhancements greatly outweigh their impact on the model's decision and should be omitted from the SINCGARS allocation determination process. A comprehensive record of these enhancements should be maintained however, because they may prove beneficial to a later upgrade effort or their present fidelity costs may be reduced by some new data source.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Computer simulation is poised on the threshold of an exciting new frontier. The continuing technological advances in computing power, both in hardware and software, have provided a software development environment that is conducive to model reuse. Object-Oriented simulation and open architecture systems are primary examples of advances that impact directly on model reuse. The diminishing requirements for model reimplementation will increase the availability of modelling effort for both new model development and the improvement of existing models. To properly navigate within this new frontier, a specialized methodology is required.

The Fidelity Enhancement Process provides a useful map for conducting the upgrade of an existing model. Although the process is directed toward models incorporating OOS and open architecture, its five stages address all of the steps necessary for a successful model upgrade. The individual stages are general enough to allow their application to a wide range of decision making models. This methodology was tested during the upgrade of the Marine Corps Communication Architecture Analysis Model(MCCAAM).

The Fidelity Enhancement Process received its initial application during the upgrade of MCCAAM. The stages proved beneficial in structuring the upgrade process to allow the rapid application of the required enhancements. The prototyping was very conducive to a group development effort in that the enhancements could be turned off to negate their impact on the remainder of the model. The fidelity analysis allowed the developers to fine tune the final model and limit the fidelity costs. The 2^k factoral design proved to be an effective technique for assessing the interactions between the enhancements as well as the main effects. The 2^k factoral experimental design provides a solid foundation for the fidelity analysis stage. The key to the continued usefulness of the Fidelity Enhancement Process is the expansion of this stage by increasing the number of different analysis techniques used.

B. RECOMMENDATIONS

The tremendous potential of model reuse warrants continued emphasis. The Fidelity Enhancement Process should be applied to more models to validate its stages and expand the number of documented fidelity analysis techniques. A greater variety of well-documented analysis strategies and techniques will increase the usefulness of the process by providing more analysis options for its users. The additional applications may also uncover the need for modifications to the stages.

The fidelity analysis stage presents the most potential for expansion or modification. Fidelity analysis is currently associated with the overall effect of an enhancement being turned on or off. Additional insight may be gained by conducting sensitivity analysis on an enhancement. This may alter the fidelity analysis or become part of the presentation of results. The actual incorporation of sensitivity analysis into the fidelity analysis is model dependent at this point, but any techniques utilized to address this issue will aid future users in tackling these problems.

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APPENDIX A: DATA

Upgrade Combination (1)		code 000	
Alternative	Grand Mean	Standard Deviation	Auto Correlation
1	4.44	1.66	.001869
2	4.44	1.66	.001869
3	4.44	1.66	.001869

	Samples					
Alternative	1	2	3	4	5	6
1	5.92	6.38	7.43	2.44	6.01	2.80
2	5.92	6.38	7.43	2.44	6.01	2.80
3	5.92	6.38	7.43	2.44	6.01	2.80

	Samples					
Alternative	7	8	9	10	11	12
1	5.52	4.77	3.63	3.15	1.69	2.55
2	5.52	4.77	3.63	3.15	1.69	2.55
3	5.52	4.77	3.63	3.15	1.69	2.55

Upgrade Combination 1	code 000

	Samples					
Alternative	13	14	15	16	17	18
1	3.10	2.83	4.57	6.90	6.52	1.76
2	3.10	2.83	4.57	6.90	6.52	1.76
3	3.10	2.83	4.57	6.90	6.52	1.76

	Samples					
Alternative	19	20	21	22	23	24
1	2.88	5.12	5.64	4.14	2.38	5.94
2	2.88	5.12	5.64	4.14	2.38	5.94
3	2.88	5.12	5.64	4.14	2.38	5.94

	Samples					
Alternative	25	26	27	28	29	30
1	3.48	3.08	5.57	5.85	6.77	4.51
2	3.48	3.08	5.57	5.85	6.77	4.51
3	3.48	3.08	5.57	5.85	6.77	4.51

T_{ijk} TABLES

UC 1	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

UC 1	Samples						Group Totals
Alternative	7	8	9	10	11	12	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

UC 1	Samples						Group Totals
Alternative	13	14	15	16	17	18	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

UC 1	Samples						Group Totals
Alternative	19	20	21	22	23	24	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

UC 1	Samples						Group Totals
Alternative	25	26	27	28	29	30	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

A_{ijl} TABLE

UC 1	Alternatives			
Group	1	2	3	Total
1	2	2	2	6
2	2	2	2	6
3	2	2	2	6
4	2	2	2	6
5	2	2	2	6

UPGRADE COMBINATION 2 RAW DATA

Upgrade Combination 2		code 001	
Alternative	Grand Mean	Standard Deviation	Auto Correlation
1	4.49	1.70	.010043
2	4.83	1.64	.018200
3	4.59	1.64	.013120

	Samples					
Alternative	1	2	3	4	5	6
1	6.14	6.00	7.49	2.78	6.32	3.16
2	5.89	6.95	7.36	4.38	6.11	3.78
3	6.45	5.86	7.43	2.81	6.40	3.75

	Samples					
Alternative	7	8	9	10	11	12
1	4.59	4.91	3.54	2.94	1.56	2.69
2	5.85	5.62	4.84	2.56	1.69	2.54
3	4.86	6.70	4.68	2.74	1.12	3.66

Upgrade Combination 2	code 001

	Samples					
Alternative	13	14	15	16	17	18
1	3.08	3.28	4.47	7.04	5.98	1.76
2	3.10	3.29	4.68	7.01	6.44	1.64
3	2.52	3.49	5.02	5.70	5.44	2.04

	Samples					
Alternative	19	20	21	22	23	24
1	2.70	5.46	6.04	5.01	2.36	5.74
2	3.55	5.12	5.86	5.46	2.38	6.20
3	3.87	5.42	4.77	5.97	3.12	6.70

	Samples					
Alternative	25	26	27	28	29	30
1	3.24	2.89	5.89	6.73	6.79	4.13
2	4.56	3.42	6.00	6.31	6.83	5.55
3	3.30	3.37	2.91	6.73	6.79	4.13

T_{ijk} TABLES

UC 2	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	0	0	0	1	0	1	2
2	1	0	1	0	1	0	3
3	0	1	0	0	0	0	1

UC 2	Samples						Group Totals
Alternative	7	8	9	10	11	12	
1	1	1	1	0	0	0	3
2	0	0	0	1	0	1	2
3	0	0	0	0	1	0	1

UC 2	Samples						Group Totals
Alternative	13	14	15	16	17	18	
1	0	1	1	0	0	0	2
2	0	0	0	0	0	1	1
3	1	0	0	1	1	0	3

UC 2	Samples						Group Totals
Alternative	19	20	21	22	23	24	
1	1	0	0	1	1	1	4
2	0	1	0	0	0	0	1
3	0	0	1	0	0	0	1

UC 2	Samples						Group Totals
Alternative	25	26	27	28	29	30	
1	1	1	0	0	.5	.5	3
2	0	0	0	1	0	0	1
3	0	0	1	0	.5	.5	2

A_{ijl} TABLE

UC 2	Alternatives			
Group	1	2	3	Total
1	2	3	1	6
2	3	2	1	6
3	2	1	3	6
4	4	1	1	6
5	3	1	2	6

UPGRADE COMBINATION 3 RAW DATA

Upgrade Combination 3		code 010	
Alternative	Grand Mean	Standard Deviation	Auto Correlation
1	5.02	1.53	.011086
2	5.18	1.62	.002872
3	5.14	1.71	.015003

	Samples					
Alternative	1	2	3	4	5	6
1	6.68	6.84	8.08	4.49	6.64	3.84
2	6.61	7.80	7.91	4.90	5.96	3.57
3	6.98	7.79	8.32	2.26	6.40	3.50

	Samples					
Alternative	7	8	9	10	11	12
1	5.31	6.60	4.60	3.68	2.76	3.08
2	5.61	6.90	4.30	4.58	1.87	4.35
3	5.19	5.41	3.74	3.99	1.88	4.24

Upgrade Combination 3	code 010

	Samples					
Alternative	13	14	15	16	17	18
1	3.83	2.86	3.58	7.02	5.67	2.37
2	3.67	3.16	5.54	7.00	6.66	1.89
3	4.59	3.81	6.00	6.76	6.82	2.25

	Samples					
Alternative	19	20	21	22	23	24
1	3.85	5.11	5.93	5.78	2.71	6.08
2	4.18	5.67	5.73	4.98	2.85	7.04
3	5.90	5.97	5.40	6.33	2.40	7.20

	Samples					
Alternative	25	26	27	28	29	30
1	4.24	4.87	6.35	5.57	7.39	4.70
2	4.30	3.88	5.00	6.92	7.18	5.29
3	4.68	3.38	5.53	5.89	7.08	4.49

T_{ijk} TABLES

UC 3	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	0	1	0	0	0	0	1
2	1	0	1	0	1	0	3
3	0	0	0	1	0	1	2

UC 3	Samples						Group Totals
Alternative	7	8	9	10	11	12	
1	0	0	0	1	0	1	2
2	0	0	0	0	1	0	1
3	1	1	1	0	0	0	3

UC 3	Samples						Group Totals
Alternative	13	14	15	16	17	18	
1	0	1	1	0	1	0	3
2	1	0	0	0	0	1	2
3	0	0	0	1	0	0	1

UC 3	Samples						Group Totals
Alternative	19	20	21	22	23	24	
1	1	1	0	0	0	1	3
2	0	0	0	1	0	0	1
3	0	0	1	0	1	0	2

UC 3	Samples						Group Totals
Alternative	25	26	27	28	29	30	
1	1	0	0	1	0	0	2
2	0	0	1	0	0	0	1
3	0	1	0	0	1	1	3

A_{ijl} TABLE

UC 3	Alternatives			
Group	1	2	3	Total
1	1	3	2	6
2	2	1	3	6
3	3	2	1	6
4	3	1	2	6
5	2	1	3	6

UPGRADE COMBINATION 4 RAW DATA

Upgrade Combination 4		code 011	
Alternative	Grand Mean	Standard Deviation	Auto Correlation
1	4.97	1.35	.014973
2	5.50	1.51	.005495
3	5.04	1.62	.007867

	Samples					
Alternative	1	2	3	4	5	6
1	6.58	6.05	6.79	4.72	6.37	4.03
2	6.46	7.68	7.82	6.04	6.15	4.08
3	7.46	5.80	6.46	3.60	6.26	4.53

	Samples					
Alternative	7	8	9	10	11	12
1	5.14	5.74	5.44	3.66	2.89	3.08
2	5.85	6.54	5.30	4.08	2.17	4.72
3	5.80	7.44	4.58	3.11	1.55	4.29

Upgrade Combination 4	code 011

	Samples					
Alternative	13	14	15	16	17	18
1	3.55	3.49	4.99	7.16	5.32	2.37
2	3.71	4.89	6.12	6.98	7.53	2.16
3	4.81	4.01	4.64	6.60	7.12	2.25

	Samples					
Alternative	19	20	21	22	23	24
1	3.85	5.32	6.17	5.93	2.70	6.09
2	4.35	5.67	5.42	6.12	2.85	6.39
3	4.64	5.94	6.02	6.85	2.68	7.37

	Samples					
Alternative	25	26	27	28	29	30
1	4.17	4.08	6.69	6.35	6.13	4.29
2	5.72	4.07	7.01	6.78	7.18	5.29
3	3.98	4.19	2.80	6.75	5.66	4.07

T_{ijk} TABLES

UC 4	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	0	0	0	0	0	1	1
2	1	0	0	0	1	0	2
3	0	1	1	1	0	0	3

UC 4	Samples						Group Totals
Alternative	7	8	9	10	11	12	
1	1	1	0	0	0	1	3
2	0	0	0	0	0	0	0
3	0	0	1	1	1	0	3

UC 4	Samples						Group Totals
Alternative	13	14	15	16	17	18	
1	1	1	0	0	1	0	3
2	0	0	0	0	0	1	1
3	0	0	1	1	0	0	2

UC 4	Samples						Group Totals
Alternative	19	20	21	22	23	24	
1	1	1	0	1	0	1	4
2	0	0	1	0	0	0	1
3	0	0	0	0	1	0	1

UC 4	Samples						Group Totals
Alternative	25	26	27	28	29	30	
1	0	0	0	1	0	0	1
2	0	1	0	0	0	0	1
3	1	0	1	0	1	1	4

A_{ijl} TABLE

UC 4	Alternatives			
Group	1	2	3	Total
1	1	2	3	6
2	3	0	3	6
3	3	1	2	6
4	4	1	1	6
5	1	1	4	6

UPGRADE COMBINATION 5   RAW DATA

Upgrade Combination 5		code 100	
Alternative	Grand Mean	Standard Deviation	Auto Correlation
1	4.15	1.58	.004884
2	4.15	1.58	.004884
3	4.15	1.58	.004884

	Samples					
Alternative	1	2	3	4	5	6
1	5.62	4.94	7.50	1.38	5.94	2.73
2	5.62	4.94	7.50	1.38	5.94	2.73
3	5.62	4.94	7.50	1.38	5.94	2.73

	Samples					
Alternative	7	8	9	10	11	12
1	4.59	4.77	3.55	2.95	1.57	2.54
2	4.59	4.77	3.55	2.95	1.57	2.54
3	4.59	4.77	3.55	2.95	1.57	2.54

Upgrade Combination 5	code 100

	Samples					
Alternative	13	14	15	16	17	18
1	3.10	2.83	4.44	6.19	6.85	1.76
2	3.10	2.83	4.44	6.19	6.85	1.76
3	3.10	2.83	4.44	6.19	6.85	1.76

	Samples					
Alternative	19	20	21	22	23	24
1	2.88	5.15	3.68	4.14	2.38	5.49
2	2.88	5.15	3.68	4.14	2.38	5.49
3	2.88	5.15	3.68	4.14	2.38	5.49

	Samples					
Alternative	25	26	27	28	29	30
1	3.25	3.08	5.57	5.85	5.24	4.46
2	3.25	3.08	5.57	5.85	5.24	4.46
3	3.25	3.08	5.57	5.85	5.24	4.46

T_{ijk} TABLES

UC 5	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

UC 5	Samples						Group Totals
Alternative	7	8	9	10	11	12	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

UC 5	Samples						Group Totals
Alternative	13	14	15	16	17	18	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

UC 5	Samples						Group Totals
Alternative	19	20	21	22	23	24	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

UC 5	Samples						Group Totals
Alternative	25	26	27	28	29	30	
1	.33	.33	.33	.33	.33	.33	2
2	.33	.33	.33	.33	.33	.33	2
3	.33	.33	.33	.33	.33	.33	2

A_{ijl} TABLE

UC 5	Alternatives			
Group	1	2	3	Total
1	2	2	2	6
2	2	2	2	6
3	2	2	2	6
4	2	2	2	6
5	2	2	2	6

UPGRADE COMBINATION 6 RAW DATA

Upgrade Combination 6		code 101	
Alternative	Grand Mean	Standard Deviation	Auto Correlation
1	4.21	1.63	.001857
2	4.50	1.53	.023120
3	4.40	1.53	.004219

	Samples					
Alternative	1	2	3	4	5	6
1	6.14	5.89	7.53	1.76	5.47	3.06
2	5.65	4.94	7.37	3.25	5.66	3.65
3	6.45	5.75	7.45	2.78	5.39	3.30

	Samples					
Alternative	7	8	9	10	11	12
1	4.59	4.91	3.54	2.94	1.67	2.69
2	4.87	5.62	4.84	2.40	1.57	2.54
3	4.86	6.70	4.68	2.74	1.12	3.66

Upgrade Combination 6	code 101

	Samples					
Alternative	13	14	15	16	17	18
1	3.08	3.28	4.44	6.33	6.34	1.76
2	3.10	3.29	4.55	6.29	6.80	1.64
3	2.52	3.49	5.02	5.60	5.44	1.96

	Samples					
Alternative	19	20	21	22	23	24
1	2.70	5.55	2.45	4.46	2.36	5.48
2	3.55	5.15	3.50	5.46	2.38	5.35
3	3.87	5.52	3.91	5.97	3.12	5.24

	Samples					
Alternative	25	26	27	28	29	30
1	3.24	2.86	5.89	6.73	5.30	4.09
2	4.31	3.42	6.00	6.31	6.06	5.51
3	3.30	3.37	2.91	6.73	5.30	4.09

T_{ijk} TABLES

UC 6	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	0	0	0	1	0	1	2
2	1	1	1	0	0	0	3
3	0	0	0	0	1	0	1

UC 6	Samples						Group Totals
Alternative	7	8	9	10	11	12	
1	1	1	1	0	0	0	3
2	0	0	0	1	0	1	2
3	0	0	0	0	1	0	1

UC 6	Samples						Group Totals
Alternative	13	14	15	16	17	18	
1	0	1	1	0	0	0	2
2	0	0	0	0	0	1	1
3	1	0	0	1	1	0	3

UC 6	Samples						Group Totals
Alternative	19	20	21	22	23	24	
1	1	0	1	1	1	0	4
2	0	1	0	0	0	0	1
3	0	0	0	0	0	1	1

UC 6	Samples						Group Totals
Alternative	25	26	27	28	29	30	
1	1	1	0	0	.5	.5	3
2	0	0	0	1	0	0	1
3	0	0	1	0	.5	.5	2

A_{ijl} TABLE

UC 6	Alternatives			
Group	1	2	3	Total
1	2	3	1	6
2	3	2	1	6
3	2	1	3	6
4	4	1	1	6
5	3	1	2	6

UPGRADE COMBINATION 7   RAW DATA

Upgrade Combination 7		code 110	
Alternative	Grand Mean	Standard Deviation	Auto Correlation
1	4.59	1.47	.001120
2	4.76	1.47	.004872
3	4.68	1.48	.003350

	Samples					
Alternative	1	2	3	4	5	6
1	6.11	6.35	6.95	1.90	6.46	3.[illegible]
2	6.14	5.20	8.02	3.77	7.14	3.13
3	6.31	5.15	7.57	2.82	5.54	2.85

	Samples					
Alternative	7	8	9	10	11	12
1	5.60	4.32	3.01	2.22	3.10	3.48
2	5.26	7.16	4.06	3.78	3.03	4.28
3	5.52	5.41	3.66	3.24	1.59	4.13

Upgrade Combination 7	code 110

	Samples					
Alternative	13	14	15	16	17	18
1	4.27	4.66	6.23	6.18	2.37	3.85
2	3.67	3.16	3.93	5.83	6.89	1.89
3	4.59	3.81	5.88	5.24	7.07	2.25

	Samples					
Alternative	19	20	21	22	23	24
1	5.04	4.59	4.66	2.70	5.53	3.49
2	4.18	5.71	4.71	4.82	2.85	5.87
3	5.84	5.77	4.35	5.35	2.40	6.36

	Samples					
Alternative	25	26	27	28	29	30
1	4.80	7.16	5.57	6.10	4.64	3.23
2	3.88	3.78	3.48	5.98	6.48	4.95
3	3.32	3.08	5.53	5.89	5.63	4.46

T_{ijk} TABLES

UC 7	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	1	0	1	1	0	0	3
2	0	0	0	0	0	0	0
3	0	1	0	0	1	1	3

UC 7	Samples						Group Totals
Alternative	7	8	9	10	11	12	
1	0	1	1	1	0	1	4
2	1	0	0	0	0	0	1
3	0	0	0	0	1	0	1

UC 7	Samples						Group Totals
Alternative	13	14	15	16	17	18	
1	0	0	0	0	1	0	1
2	1	1	1	0	0	1	4
3	0	0	0	1	0	0	1

UC 7	Samples						Group Totals
Alternative	19	20	21	22	23	24	
1	0	1	0	1	0	1	3
2	1	0	0	0	0	0	1
3	0	0	1	0	1	0	2

UC 7	Samples						Group Totals
Alternative	25	26	27	28	29	30	
1	0	0	0	0	1	1	2
2	0	0	1	0	0	0	1
3	1	1	0	1	0	0	3

A_{ijl} TABLE

UC 7	Alternatives			
Group	1	2	3	Total
1	3	0	3	6
2	4	1	1	6
3	1	4	1	6
4	3	1	2	6
5	2	1	3	6

UPGRADE COMBINATION 8 RAW DATA

Upgrade Combination 8		code 111	
Alternative	Grand Mean	Standard Deviation	Auto Correlation
1	4.68	1.56	.001330
2	5.13	1.47	.003980
3	4.87	1.56	.008338

	Samples					
Alternative	1	2	3	4	5	6
1	6.78	6.05	7.09	1.72	6.58	3.50
2	6.37	5.12	7.84	5.10	7.27	3.53
3	7.16	5.75	7.44	3.48	6.22	4.15

	Samples					
Alternative	7	8	9	10	11	12
1	3.30	5.97	5.02	3.45	2.20	4.28
2	5.50	6.34	5.37	3.96	2.15	4.26
3	5.80	6.49	5.79	4.58	3.11	1.19

Upgrade Combination 8	code 111

	Samples					
Alternative	13	14	15	16	17	18
1	2.82	4.73	4.65	6.37	6.73	2.23
2	3.71	3.79	6.27	6.73	6.84	1.89
3	4.13	4.60	4.00	6.41	7.12	2.24

	Samples					
Alternative	19	20	21	22	23	24
1	3.85	5.41	4.68	6.09	2.70	5.87
2	4.03	5.71	4.88	6.48	2.85	5.95
3	4.57	5.74	5.17	5.61	3.13	6.66

	Samples					
Alternative	25	26	27	28	29	30
1	3.05	3.90	7.16	5.56	4.07	4.75
2	4.34	4.03	7.01	5.94	5.79	4.94
3	4.20	3.37	2.80	6.75	4.37	4.07

T_{ijk} TABLES

UC 8	Samples						Group Totals
Alternative	1	2	3	4	5	6	
1	0	0	1	1	0	1	3
2	1	1	0	0	0	0	2
3	0	0	0	0	1	0	1

UC 8	Samples						Group Totals
Alternative	7	8	9	10	11	12	
1	1	1	1	1	0	0	4
2	0	0	0	0	1	0	1
3	0	0	0	0	0	1	1

UC 8	Samples						Group Totals
Alternative	13	14	15	16	17	18	
1	1	0	0	1	1	0	3
2	0	1	0	0	0	1	2
3	0	0	1	0	0	0	1

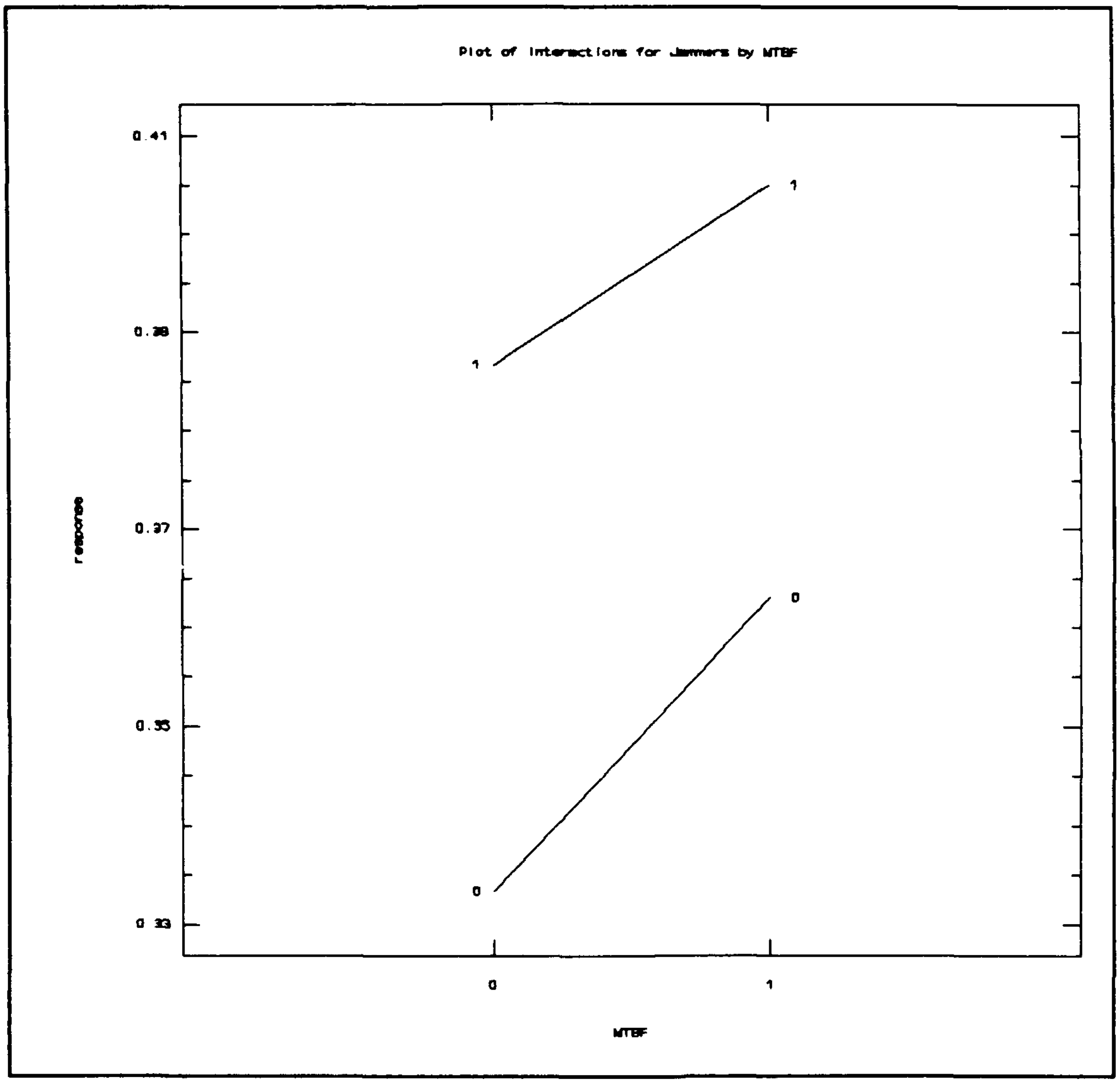
UC 8	Samples						Group Totals
Alternative	19	20	21	22	23	24	
1	1	1	1	0	1	1	5
2	0	0	0	0	0	0	0
3	0	0	0	1	0	0	1

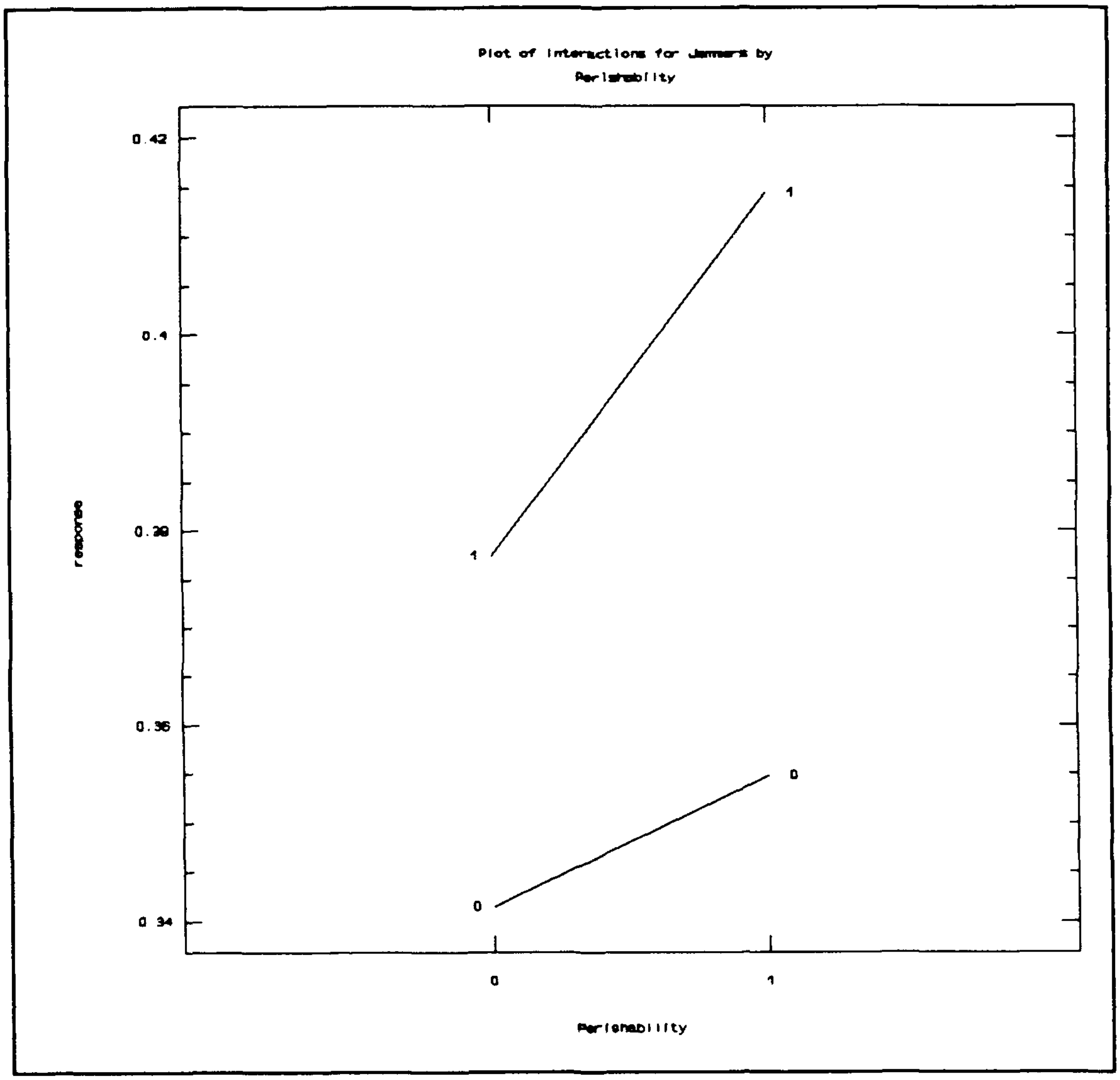
UC 8	Samples						Group Totals
Alternative	25	206	27	28	29	30	
1	1	0	0	1	1	0	3
2	0	0	0	0	0	0	0
3	0	1	1	0	0	1	3

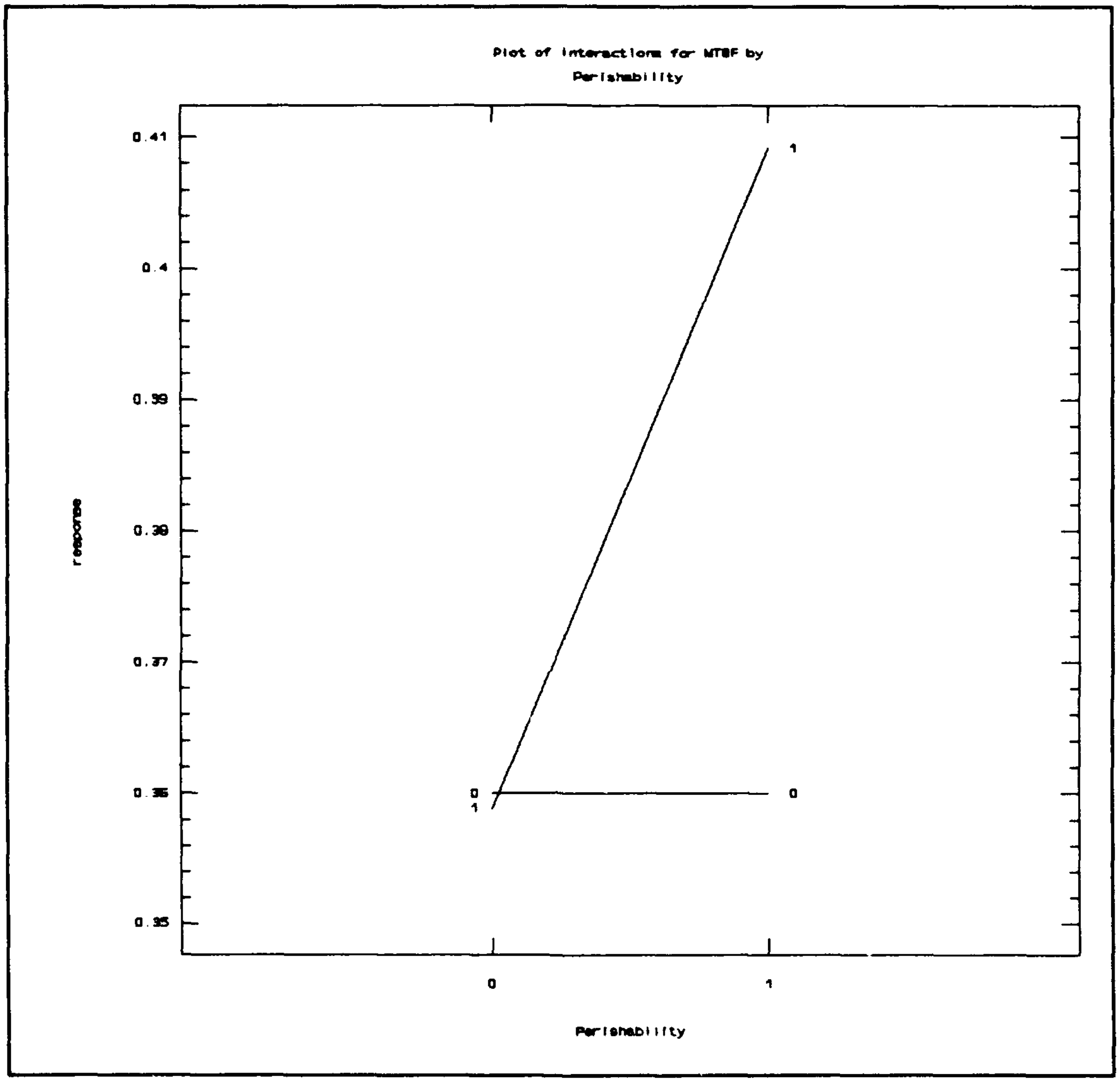
A_{ijl} TABLE

UC 8	Alternatives			
Group	1	2	3	Total
1	3	2	1	6
2	4	1	1	6
3	3	2	1	6
4	5	0	1	6
5	3	0	3	6

APPENDIX B: INTERACTION PLOTS




Plot of Interactions for Jammers by
Perishability
0.42
0.4
0.38
0.36
0.34
response
1
1
0
0
0
1
Perishability



Plot of Interactions for MTBF by
Perishability
0.41
0.4
0.39
0.38
0.37
0.36
0.35
response
0
1
Perishability

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